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MICROSTRUCTURE AND SELECTED MECHANICAL PROPERTIES OF HOT-ROLLED AA2024/SiC COMPOSITE MANUFACTURED BY POWDER METALLURGY

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This study investigates the microstructure and mechanical properties of an AA2024/SiC composite produced using powder metallurgy, followed by hot extrusion and multi-pass hot rolling. The composite, containing 5 wt% SiC, was fabricated by hot pressing at 450°C, then extruded and rolled with reductions of up to 66.2%. Microstructural analysis revealed uniform distribution of the SiC particles, grain refinement due to dynamic recrystallization (DRX), and enhanced particle dispersion with increasing rolling reduction. The hardness measurements showed significant improvement, with values increasing from 91 HV1 in the extruded state to 112 HV1 after the final rolling pass, and further grew to 151 HV1 after heat treatment. The tensile tests confirmed a strengthening effect, with the yield stress and ultimate tensile strength rising with rolling reduction from 205 MPa and 304 MPa (after initial rolling) to 236 MPa and 352 MPa (after the final rolling), respectively. Solution treatment and aging of the rolled composite resulted in a sharp increase in yield stress and ultimate tensile strength, reaching 293 MPa and 431 MPa after the first pass, increasing to 375 MPa and 484 MPa after the final pass. The study concludes that hot rolling significantly enhances the mechanical performance of AA2024/SiC composites, with grain refinement and particle fragmentation playing key roles in the strengthening mechanisms.

Keywords: composite, AA2024 alloy, SiC, hot extrusion, hot rolling, microstructure, mechanical properties

INTRODUCTION

Aluminum-based composites show great potential for applications in industries such as automotive, aerospace, and space exploration, resulting from their good combination of properties and relatively low production costs. Research on aluminum-based composites has been ongoing for several decades and will continue to be of interest. There is an extensive body of literature on metal matrix composites reinforced with particles such as B_4C [1–2], Al_2O_3 [3–5], AlN [6–9], TiB_2 [10–13], TiC [14–17], or fly ash [18–20]. A particular focus has been given to composites reinforced with silicon carbide (SiC) [21–41]. The addition of SiC particles to aluminum or its alloys provides good wear resistance, high thermal conductivity, and the ability to increase the strength of the composite. It is also relatively inexpensive compared to other reinforcements used for manufacturing composites. The mechanical properties of metal matrix composites can be controlled by the particle type, volume fraction, shape, and size of the particles.

Particle-reinforced composites are produced by means of casting methods and powder metallurgy techniques. The casting methods include squeeze casting [2, 18, 19, 27, 28], and stir casting [16, 18, 19, 29, 30]. The powder metallurgy methods include pressing and sintering [31], hot pressing [1, 9, 20], spark plasma sintering [3, 4], or additive manufacturing, such as the laser powder bed fusion process (LPBF) [13, 32]. Low-temperature solid-state powder processes eliminate reactions between the reinforcement particles and the matrix, which are indeed an important problem with methods involving molten metal [33–34].

Composites made from powders are porous, and their density can be increased by applying plastic deformation, thereby enhancing their mechanical properties. Particle-reinforced composites can successfully be processed hot in forging [35], extrusion [5, 6, 34, 36–48], or rolling [39, 41], or they can also be cold rolled or drawn [37, 38, 40], which leads to a significant increase in their strength.

The aim of this study is to investigate the effect of hot rolling and heat treatment on the microstructure and mechanical properties of the AA2024/SiC composite produced from powders by means of hot pressing and extrusion.

MATERIALS AND METHODS

The AA2024/SiC composite was prepared using powder metallurgy by hot pressing. The compacts were then subjected to plastic deformation processing via hot extrusion and rolling. The AA2024 powder used in the composite was commercially sourced from Avimetal Powder Metallurgy Technology Co., Ltd., with powder characteristics provided by the manufacturer. The chemical composition of the alloy powder is presented in Table 1. This powder had particle sizes in the range of 45-106 μm. SiC particles from the F800 fraction, with an average particle size of 6.5 μm, were used.

TABLE 1. Chemical composition of AA2024 powder

Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Al
0.42	0.36	4.01	0.78	1.53	0.04	0.07	0.06	Bal.

The ultrafine-grained microstructure of the AA2024 powder and the hardness indentation on the powder cross-section are shown in Figure 1a and b, respectively. The microhardness of the atomized AA2024 powder was 120±7.7 HV0.01.

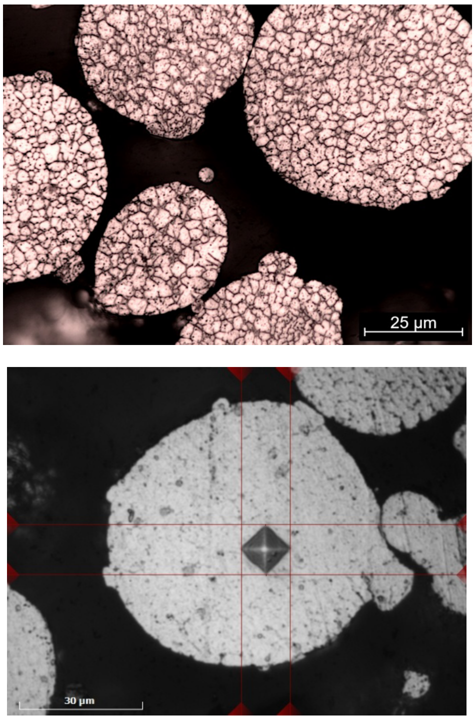


Fig. 1. Microstructure of AA2024 powder (a) and microhardness indentation on powder particle cross-section (b)

The powder mixture, consisting of 95 wt% AA2024 and 5 wt% SiC, was prepared in a double-cone mixer. The mixing time was 1 hour.

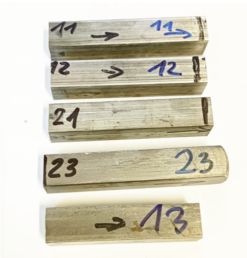
Hot pressing and extrusion

The mixture was then hot-pressed under isothermal conditions at the temperature of 450°C and pressure of 80 MPa. Figure 2 presents the resulting compacts, which had a diameter of 39.9 mm and a height of approximately 37.5 mm. The average density of the compacts, determined using the geometrical method and confirmed by the Archimedes method was 2.771 g/cm³.

Fig. 2. Hot-compacted samples of AA2024/SiC composite

Forward extrusion of the AA2024/SiC compacts was carried out on a hydraulic press using an extrusion die with a square 14x14 mm orifice. The process was conducted under isothermal conditions at 450°C. The extrusion ratio was 6.4. Samples before and after extrusion are displayed in Fig. 3. The prepared samples had a length of ~200 mm. Before rolling, each sample was cut into three parts.

a)



b)

Fig. 3. Samples before and after extrusion (a) and cut specimens prepared for rolling (b)

Hot rolling

The rolling process of the previously extruded samples was performed on a quarto rolling mill. Prior to rolling, the samples were heated for 30 minutes in an electric furnace. The rolling process consisted of 11 passes, with a rolling reduction of approximately 10% in each pass. Before each subsequent pass, the samples were reheated for 5 minutes at the temperature of 450°C. The process scheme is shown in Figure 4.

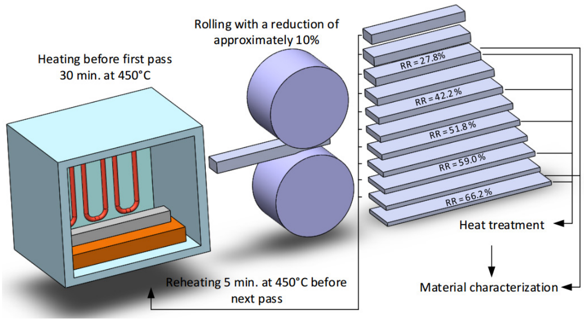


Fig. 4. Rolling process scheme

Material characterization after rolling was performed on samples after 3, 5, 7, 9, and 11 passes. Data such as the sample height after rolling, reduction in individual passes, and total reduction are presented in Table 2.

TABLE 2. **Thickness of samples after each pass in rolling process and corresponding reductions**

Pass number	Thickness after deformation, mm	Reduction in individual passes, %	Total reduction RR, %	Designation of samples left for microstructure and mechanical properties testing
1	12.30	11.5	11.5	-
2	11.18	9.1	19.6	-
3	10.04	10.2	27.8	W1
4	8.98	10.6	35.4	-
5	8.04	10.5	42.2	W2
6	7.30	9.2	47.5	-
7	6.70	8.2	51.8	W3
8	6.20	7.5	55.4	-
9	5.70	8.1	59.0	W4
10	5.26	7.7	62.2	-
11	4.70	10.6	66.2	W5

The average density of the composite, determined by the Archimedes method, increased to 2.795 g/cm³ after hot extrusion and further to 2.797 g/cm³ following hot rolling with a 66.2% reduction.

Heat treatment

The selected specimens were heat-treated after rolling. Solution treatment was carried out at 480°C for 2 hours, followed by artificial aging at 180°C for 6 hours.

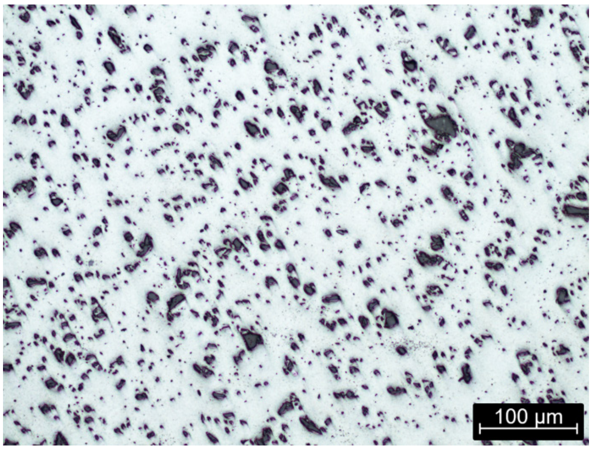
Material testing methods

AA2024/SiC was subjected to microstructure, hardness, and tensile testing. Microstructural examinations were conducted by means of a Leica DM4000M light microscope. Microstructure documentation was performed for both unetched and etched specimens, utilizing Keller's reagent (190 ml of distilled water, 5 ml of nitric acid, 2 ml of hydrofluoric acid, and 3 ml of hydrochloric acid) and Weck's reagent (100 ml of distilled water, 4 g of potassium permanganate, and 1 g of sodium hydroxide). Grain size analysis was performed by employing the ImageJ program on the etched microstructure micrographs for both the extruded state and after rolling. Hardness measurements were taken using a Struers DURAMIN-40 M1 hardness tester. The material was tested in the extruded state, after rolling, and after rolling followed by heat treatment. Hardness measurements were taken at randomly selected locations, with five indentations made per location. Tensile tests of the samples were conducted by means of a Zwick/Roell Z250 testing machine. These tests were performed both in the as-rolled state as well as after rolling and heat treatment.

RESULTS AND DISCUSSION

Microstructure

The unetched microstructure showing the distribution of SiC in the matrix of the extruded composite is presented in Fig. 5. The distribution of SiC in the matrix is relatively uniform, both in the cross-sectional (Fig. 5a) and longitudinal (Fig. 5b) directions along the extrusion direction. Larger agglomerations are visible in some areas. A band-like distribution of carbides in the matrix along the extrusion direction is also observed. The deformation of the matrix during extrusion contributed to the fragmentation of larger SiC particles, with the fragmented larger particles highlighted in Fig. 5b.



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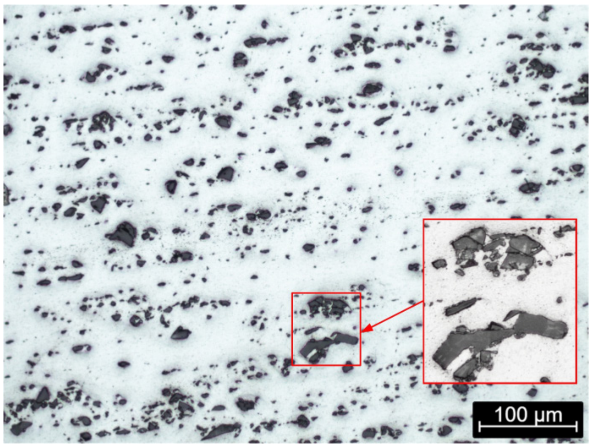
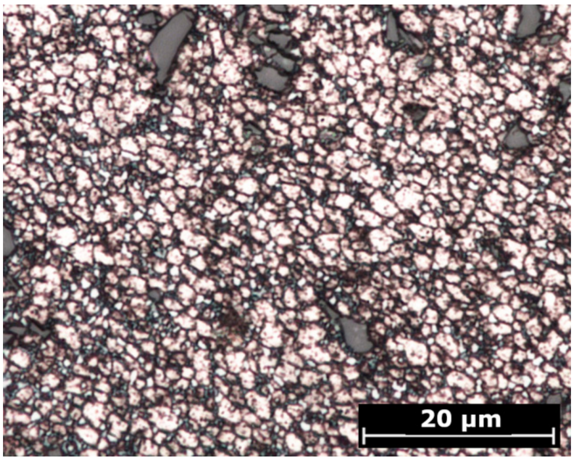


b)

Fig. 5. Distribution of SiC in matrix after hot extrusion: a) cross-section, b) longitudinal section along extrusion direction

The Weck-etched matrix microstructure of the extruded composite is presented in Fig. 6. Comparing the microstructure to the powder microstructure (Fig. 1a), it can be observed that grain refinement occurred during the extrusion process. In the cross-sectional view (Fig. 6a), the grains are nearly equiaxed, while in the longitudinal direction (Fig. 6b), they are elongated in the direction of material flow.



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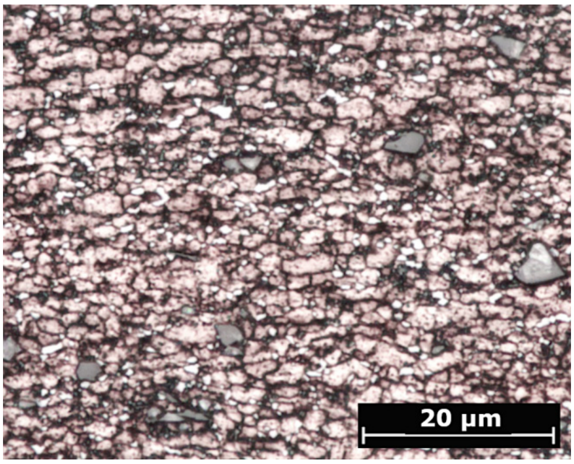
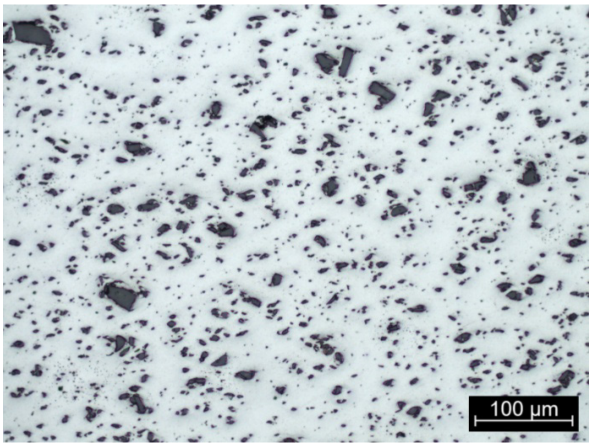


b)

Fig. 6. Etched microstructure of extruded composite: a) cross-section and b) longitudinal section in extrusion direction

The distribution of SiC particles in the matrix after rolling with reductions of 27.8% and 66.2% is presented in Figures 7 and 8, respectively. Further plastic deformation of the extruded composite resulted in additional fragmentation of the SiC particles, leading to an increased number of very fine SiC particles. As a result, a more uniform distribution of SiC in the matrix was achieved. However, in the longitudinal section, the characteristic banded arrangement of SiC particles is still visible.



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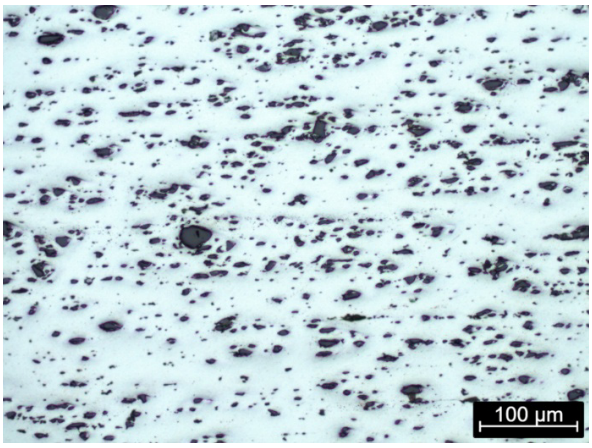
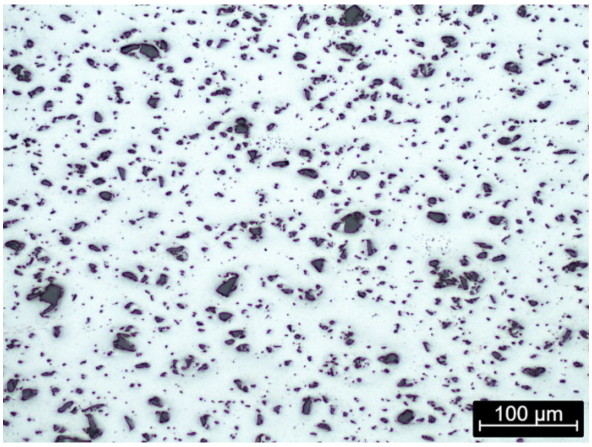


b)

Fig. 7. Distribution of SiC in matrix after hot extrusion and hot rolling with reduction of 27.8%: a) cross-section, b) longitudinal section along extrusion and rolling directions.



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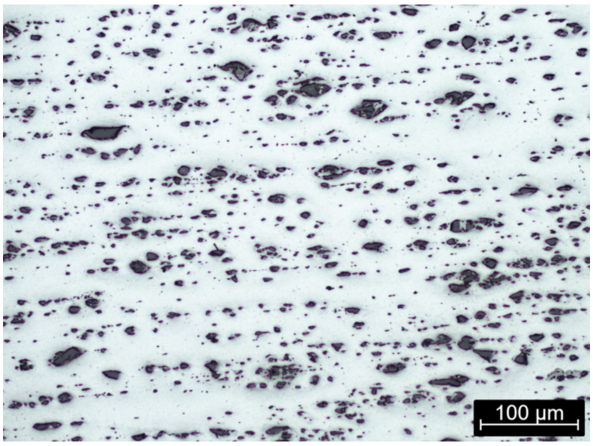

b)

Fig. 8. Distribution of SiC in matrix after hot extrusion and hot rolling with reduction of 66.2%: a) cross-section, b) longitudinal section along extrusion and rolling directions.

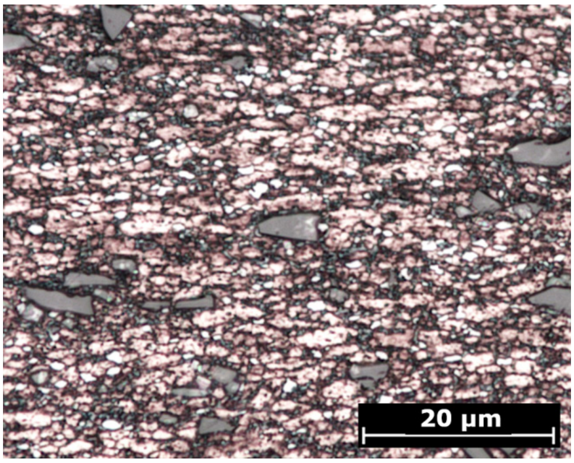

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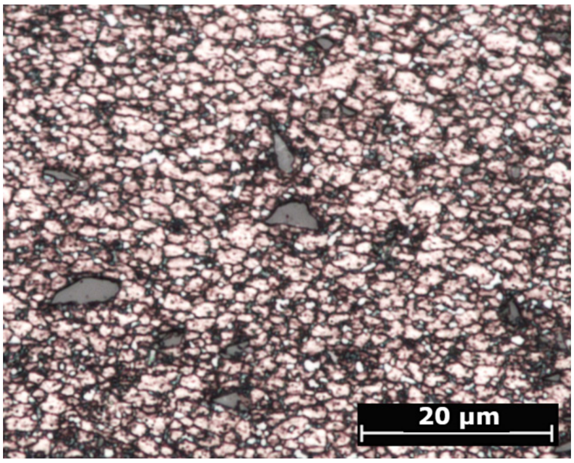
Fig. 9. Etched microstructure of hot-extruded and hot-rolled composite with reduction of 27.8%: a) cross-section, b) longitudinal section along extrusion and rolling directions.

The etched matrix microstructure of the hot-extruded and hot-rolled composite with reductions of 27.8% and 66.2% is presented in Figures 9 and 10, respectively. As a result of the rolling process, significant grain refinement of the matrix occurred via dynamic recrystallization (DRX). The greater the rolling reduction, the finer the grain. In the cross-sectional view, the grains are nearly equiaxed, while in the longitudinal section, they are slightly elongated in the direction of material flow. It can also be observed that the grains are finer in the vicinity of the SiC particles.



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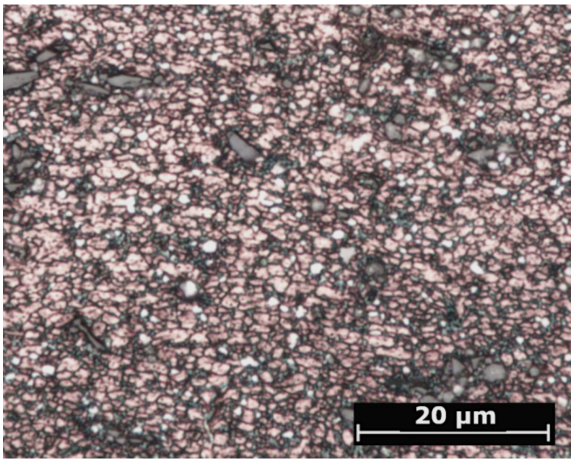

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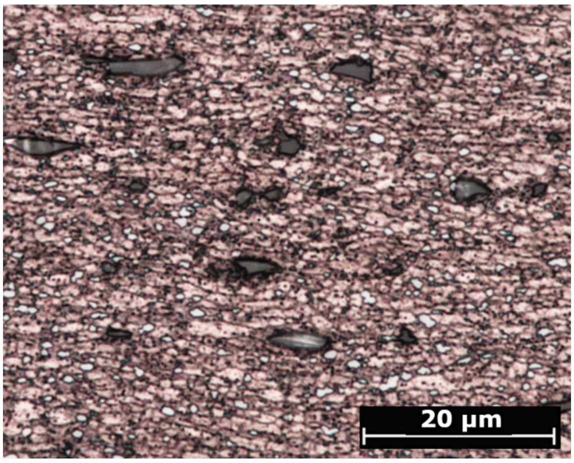

b)

Fig. 10. Etched microstructure of hot-extruded and hot-rolled composite with 66.2% reduction: a) cross-sectional, b) longitudinal direction along extrusion and rolling directions

A detailed grain size analysis of the matrix was performed based on microstructure images using the ImageJ program for the material after hot extrusion and after hot rolling, following the first and final passes. The results are presented in Fig. 11. As mentioned earlier, the grain size decreases with each stage of plastic deformation. The average grain size after extrusion was 2.54 μm, after the first pass in the rolling process (RR = 27.8%) it was 1.87 μm, and after the final pass (RR = 66.2%) it was 1.47 μm. As can be observed in Fig. 11, the distributions narrow after each stage of plastic deformation, resulting in a more uniform grain structure.

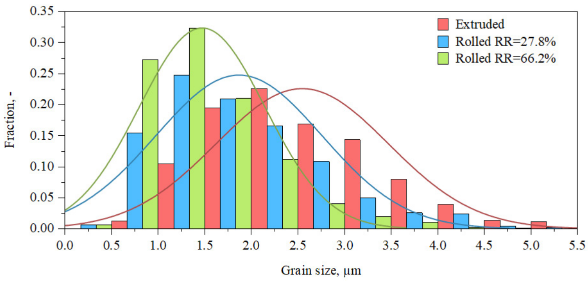

Fig. 11. Grain size distribution in cross-section for extruded and hot-rolled samples

The microstructure of the AA2024/SiC composite etched with Keller's reagent after hot rolling (final pass) and subsequent heat treatment is presented in Fig. 12. It is characterized by very fine precipitates with no visible grain boundaries.

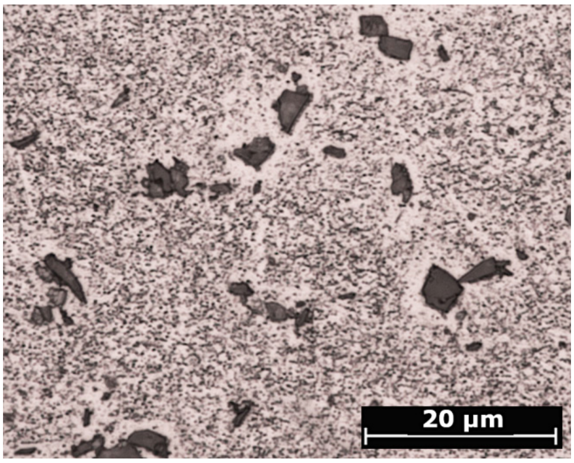

Fig. 12. Etched microstructure on cross-section of hot-rolled composite with 66.2% reduction and heat treatment

Hardness

The average hardness of the AA2024/SiC composite in the extruded state was 91 HV1. Further processing of the material by rolling resulted in a rise in hardness. After the first pass, the hardness grew to 101 HV1, and after the final pass it reached 112 HV1. Heat treatment caused a significant increment in hardness, which rose to 136 HV1 for the composite rolled in a single pass and to 151 HV1 for the composite after the final pass. The relationship between the hardness and rolling reduction for the composite in the as-rolled state as well as after rolling and heat treatment is shown in Fig. 13.

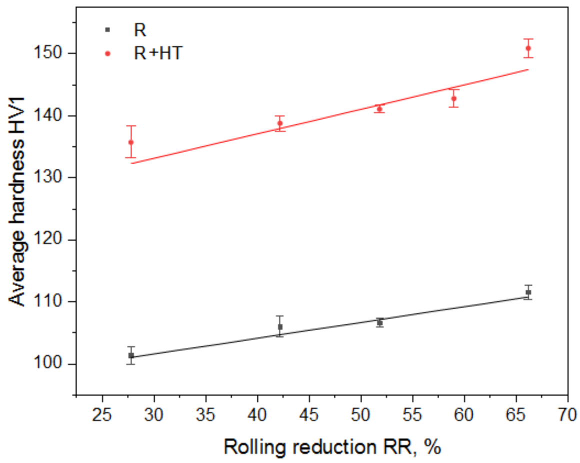

Fig. 13. Relationship between average hardness, rolling reduction, and effect of applied heat treatment

In the case of the heat-treated composite, a similar growing trend in hardness with respect to rolling reduction was observed, as seen in the composite in the as-rolled state.

Results of tensile tests

The engineering stress-strain curves from the tensile tests for the Al/SiC composite in the as-rolled state and after rolling and heat treatment are presented in Fig. 14.

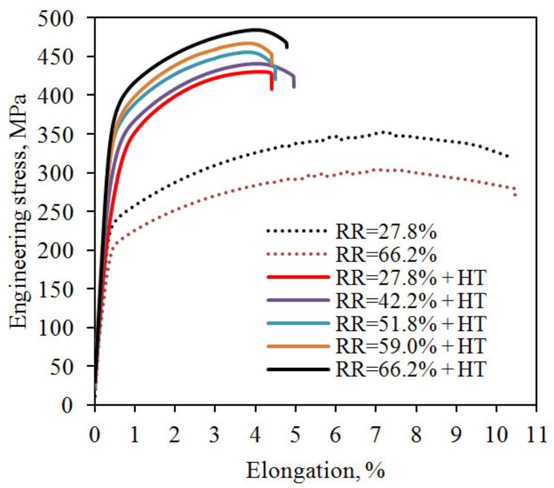

Fig. 14. Engineering stress – elongation for hot rolled and heat treated AA2024/5SiC composite

The data from the tensile test are presented in Table 3. The yield stress of the composite after the first pass in the rolling process was 205 MPa, and the ultimate tensile strength was 304 MPa. After the final pass in the rolling process, the YS grew to 236 MPa, and the UTS rose to 352 MPa. Heat treatment significantly affected the increment in the strength properties and the decrease in ductility. The yield stress increased to 293 MPa and 375 MPa for the heat-treated composite after the first and final rolling passes, respectively. The UTS grew to 431 MPa and 484 MPa for the heat-treated composite after the first and final rolling passes, respectively. The relationship between YS and UTS with rolling reduction is shown in Fig. 15. In the case of elongation, no downward trend was observed; the elongation remained comparable, ranging from 3.8% to 4.4%.

TABLE. 3. Mechanical properties of hot rolled and heat treated composite

No.	Process	RR, %	YS, MPa	UTS, MPa	El, %
1	Rolling R	27.8	205	304	10.1
2		66.2	236	352	9.8
3	Rolling + heat treatment R+HT	27.8	293	431	3.8
4		42.2	333	440	4.4
5		51.8	358	455	3.9
6		59.0	365	467	3.8
7		66.2	375	484	4.2

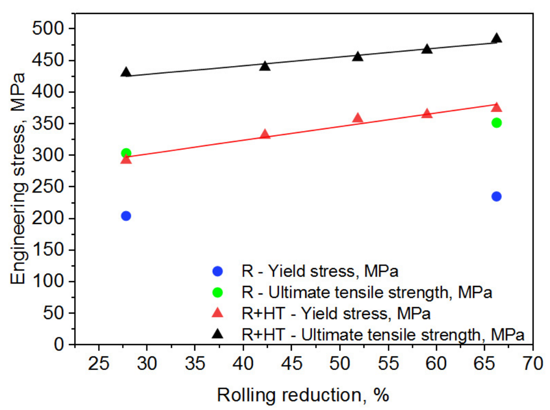

Fig. 15. Effect of rolling reduction and heat treatment after rolling on yield stress, ultimate tensile strength of AA2024/SiC composite

As in the case of hardness (Fig. 13), a growing trend in the mechanical properties of YS and UTS can be observed with increasing rolling reduction. The increase in YS and UTS is associated with microstructural changes, such as grain and particle refinement after successive rolling stages. Similar relationships were obtained in the studies of Z. Wang et al. in [41], but the strengthening effect of the AA2009/15%SiC composite produced by powder metallurgy was observed only up to an RR of 70%; further reduction led to a decline in composite strength. On the other hand, Luo et al. [39] demonstrated in their research that for the

A356/5SiCp composite produced by the stir casting method, the mechanical properties continued to improve with increasing rolling reduction up to 90%. In both the mentioned studies, the authors also reported significant microstructural refinement occurring due to dynamic recrystallization (DRX) after successive passes during the hot rolling process.

CONCLUSIONS

The combination of hot pressing and hot extrusion resulted in an AA2024/SiC composite with a density close to that of solid material. The microstructure of the composite in the extruded state was characterized by very fine grains and a uniform distribution of SiC in the matrix, without significant agglomeration. Based on the conducted research, key conclusions were drawn after the subsequent stage of plastic deformation via hot rolling.

- Hot rolling significantly refined the microstructure, leading to a reduction in the matrix grain size and fragmentation of larger SiC particles. As a result, the composite exhibited a more uniform microstructure with a narrower grain size distribution. The refinement effect became more pronounced with increasing rolling reduction, with the highest degree of uniformity observed at a 66.2% reduction.
- Microstructural refinement positively impacted the mechanical properties of the composite. The hardness, yield strength YS, and ultimate tensile strength UTS grew with increasing rolling reduction, while elongation remained comparable regardless of the rolling reduction.
- Heat treatment resulted in a significant increase in the strength properties, while maintaining the correlation with rolling reduction.
- The combined processing approach of hot extrusion, hot rolling, and heat treatment effectively optimized the properties of the AA2024/SiC composite. The study confirms that controlled plastic deformation and heat treatment can significantly enhance the mechanical properties of aluminum-based metal matrix composites, making them more suitable for high-performance applications.

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